Over-the-Horizon Communications System for UAVs based on Intelligent Antennas

Yawei Mu(1,2), Rodrigo Blázquez García(2), Jaime Aguareles Palomar(2), Xiaoliang Sun(2), Alejandro García Tejero(2), José Manuel Fernández González(2), Mateo Burgos García(2), Manuel Sierra Castañer(1)

muyawei822@gmail.com, rodrigo.blazquez.garcia@alumnos.upm.es, jaguareles@usol.es, x.sun@alumnos.upm.es, alejandro.gtejero@alumnos.upm.es, jmfdez@gr.ssr.upm.es, mateo.burgos@upm.es, manuel.sierra@upm.es

(1) School of Information and Electronics, Beijing Institute of Technology. Beijing 100081, P. R. China.

(2) Dpto. de Señales, Sistemas y Radiocomunicaciones. Universidad Politécnica de Madrid. Av. Complutense, 40. Ciudad Universitaria, 28040, Madrid.

(3) Unmanned Solutions, S. L. Calle Milán, 34, bajo. 28043, Madrid.

***Abstract*- Nowadays, the communication links limit the autonomy of Unmanned Aerial Vehicles (UAV). In this paper, a multichannel long-range communication link for UAVs with high quality of service, moderate bandwidth and affordable cost is proposed. This link is deployed by using a second UAV as a communications relay and it provides bidirectional coverage for telemetry and telecommand and a high-capacity downlink for video. Our highly compact system can be installed on medium-sized UAVs for air-air links in order to offer greater flight autonomy. This system is based on an active circular array of linearly polarized circular patch antennas which are selectively activated depending on the desired direction of the beam.**

I. INTRODUCTION

The autonomy of unmanned aerial vehicles (UAV) is currently limited by the communications links used for sending telecommands and the data captured by the sensors of the airborne platform. Using an S, C or K band line-of-sight radio link is the most common strategy. However, these links imply reduced autonomies which are highly dependent on the terrain orography. A second possibility is the usage of a satellite connection. In this case, either a very expensive space segment or an Iridium-like system is used. The former is not economically feasible for small and medium-sized UAVs whereas the latter has communication outages and an insufficient quality of service for this application. Therefore, the current state of UAV communications is that data links have short ranges, high costs, low capacity or low reliability.

In this paper, a multichannel long-range communication link with high quality of service, moderate bandwidth and affordable cost is proposed. The objective is to achieve a 70 km range. As shown in Fig. 1, this link is deployed by using a second UAV as a communications relay. This UAV is kept close to the ground station to guarantee the line-of-sight connectivity, and at a sufficient altitude to avoid terrain obstacles that can block the link between the UAVs. The communications system has to provide bidirectional coverage for telemetry and telecommand, and a high-capacity downlink for video or equivalent sensors.

The key point of the aerial link is the radiating system. The usage of a narrow beam antenna in both UAVs increase significantly the range of the system. The main problem that arises is to keep both antennas pointed for any relative position and any flight attitude of the UAVs. Besides, commercial-off-the-self (COTS) devices for radio links at C band (5 GHz) are going to be used because the imminent normalization of this band will promote the development of equipment with good price-performance ratio.

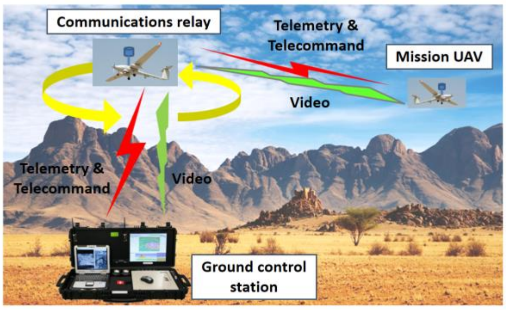

Fig. 1. Long-range UAV-relay system

This solution will provide a greater flight autonomy for UAVs than the current ones. Several advances have been achieved in this regard, but none of them with the extent addressed in this innovative system. The application of smart antennas with tracking systems for ground stations [1] has been developed during the last few years, and they are in operation for medium-sized and large systems. However, there hardly exist any similar systems for airborne platforms.

A communications system with smart antennas for UAVs is analysed theoretically in [2], but it is not physically implemented due to the high complexity of the design. A solution that has been implemented is shown in [3] as an emerging technology identified by the European Space Agency. However, the limitations of this system make it unfeasible for the application depicted in Fig. 1. It can be applied only in air-ground links of UAVs with a high attitude stability and it has a limited pointing margin.

Our proposed system is highly compact and can be installed on medium-sized UAVs for air-air links with medium gain antennas. In addition, it can be pointed over a 360º azimuth range for any attitude of the UAVs.

II. SYSTEM ARCHITECTURE

The system architecture admits certain level of freedom, and then simplicity has been taken into account above all.

The frequency band designated for the system is the C band, particularly from 5030 to 5091 MHz.

As shown in Fig. 2, our system consists of three modules: a common module that controls and manages the system and includes the modems; T/R modules that receive and transmit the signal to each antenna; and the antennas, that are composed of two circular arrays with eight patches each.

The common module includes two modems, one for control and another for data transmission. Both of them employ TDD to separate transmission and reception and must work in different frequency bands so that they do not interfere with each other. This is a critical point because the signal transmitted by the modems can be considerably bigger than the signal received. The system uses a bandwidth of 80 MHz. The modems use spread spectrum, which allows the system to work with low SNR levels. The control modem receives and sends telemetry, telecommands, location and system information; it has a bidirectional link with narrow bandwidth. The data modem streams the video captured with the UAV camera so it can be showed at the ground station. This link is bidirectional and quite asymmetrical.

The modem signals go to a 3dB coupler, which separates receiver and transmitter systems. It is essential a good isolation in the coupler in order to avoid interferences from port 1 to 2, between modems, and from 3 to 4, between reception and transmission. For this reason, it is required about 30 dB isolation. After that, in transmission part there is a π attenuator to give certain margin to avoid saturation of the transmission amplifiers if modems use a high power. In addition, an eight-way-power-divider leads the signal towards each T/R module of the antenna. As a security measure, the receiver has a power limiter connected to the port 3 of the coupler to avoid high power levels coming from the modems that could damage the following components.

The next module is the transceiver block. Despite of the fact that Rx and Tx antennas are different, the module is common to each antenna pair. This solution reduces by half the number of circuit boards to assemble. In this module, it is included the power circuits which are separated to avoid coupling between transmission and reception. They provide DC voltage to active components. In addition, the control circuits decide which of the patches are connected in order to obtain the desired radiation pattern.

Transmission chain includes a high power amplifier that provides the antenna with enough power without saturation. It also incorporates a band pass filter from 5 to 5.8 GHz to avoid possible interferences with other systems.

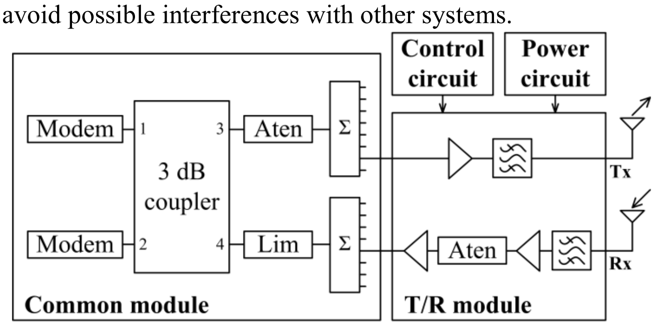

Fig. 2. Complete system architecture

Receiver module is more complex. First, there is a band pass filter that is similar to the transmission filter and it removes the non-desirable frequency components from the antenna signal. Second, a low noise amplifier increases the power of signal and avoids degradation of the noise factor of the system. After that, there is a π attenuator that provides the module with a certain level of freedom since it is adjustable and can regulate the chain gain. Following it we can find the final amplifier with a high P1dB in order to avoid saturation in the chain.

Finally, the smart antenna module is based on two circular arrays, one for reception and the other for transmission, in order to guarantee a good isolation between transmitter and receiver channels. Each array consists of eight patches, although only two or three patches are activated together. A microcontroller decides which ones work depending on the second UAV position. To avoid problems with vibration in aerial conditions, T/R circuit boards and patch antenna boards are assembled together.

III. ANTENNA SYSTEM DESIGN

A. Antenna element

The designed transmitter and receiver antennas are composed of a circular array of eight elements. The microstrip vertically polarized circular patch antenna is used as the basic radiating element due to its advantages of small size, low profile, simple geometry and low cost [4]. Fig. 3 shows the geometry of one element. It consists of one circular patch, whose radius is 13.7 mm, a circular feeding disk stacked between three substrate layers and a rectangular ground plane. The lengths and widths of three substrates and the ground plane are all 58x30 mm. The top substrate is a 0.254 mm-thick FR4 followed by a 3 mm-thick FOAM. The following layers staked at the bottom of the FOAM are respectively a 4 mm-thick aluminium and a 0.5 mm-thick Taconic 5A, whose relative permittivity (ϵ_r) is 2.17. On this last substrate, the feeding and T/R circuits are mounted. The copper feeding disc is connected to the centre conductor of a coaxial cable, which is located at a distance of 5.7 mm from the centre of the circular patch. Besides, two planes made of aluminium are used at the top and bottom to reduce the undesirable electromagnetic interference from the other array and improve the isolation between receiver and transmitter. Their length is 20.5 mm.

The antenna operates at 5.065 GHZ. One radiating element has been simulated in CST to optimize the return loss. As presented in Fig. 4, a bandwidth of 110 MHz, which is enough to cover the working band, is achieved. The vertical plane radiation pattern of one element is represented in Fig. 5, from which it can be observed that HPBW (Half Power Beam Width) in elevation is about 50.7º, which satisfies our requirement for one patch antenna.

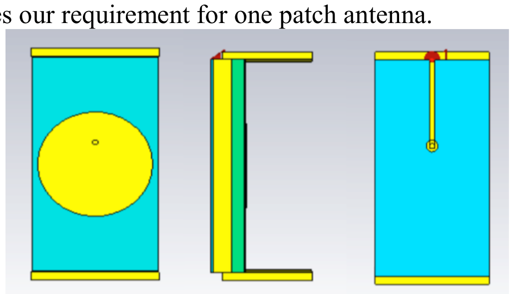

Fig. 3. Geometry of the proposed patch antenna

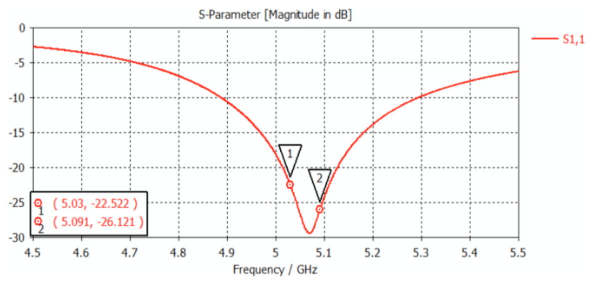

Fig. 4. Simulated S_{11} parameter for an array element

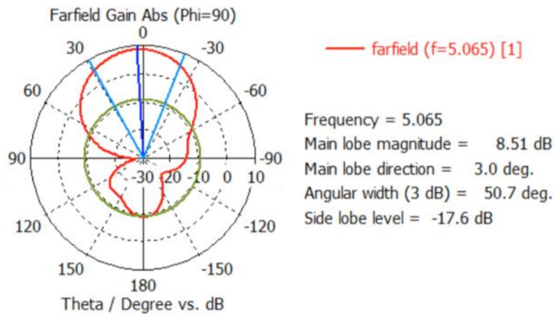

Fig. 5. Simulated radiating pattern for an element (vertical plane)

Fig. 6 represents the geometry of a 2x2 element configuration including both transmitter and receiver antennas. To get a better analysis, every element is given a number. The transmitter and receiver antennas are separated by aluminium material. The optimized S parameter simulation results, when only one element is activated, are depicted in Fig. 7 in order to show the isolation between transmitter and receiver elements. In the considered bandwidth, a return loss for each individual element better than 20 dB and an isolation better than 35 dB between transmitting and receiving elements are achieved. The radiation pattern normalized to the total input power is shown in Fig. 8 for both horizontal and vertical planes. Because there are 8 elements, each 2x2 configuration should cover 45º. HPBW is 46.1º in horizontal plane and 52.2º in vertical plane, which are suitable for both dimensions.

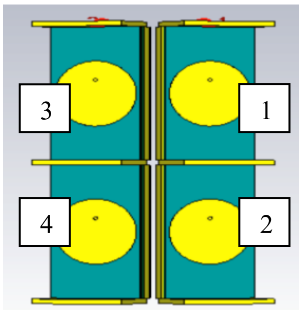

Fig. 6. Geometry of 2x2 elements for transmitter (the upper two) and receiver (the lower two)

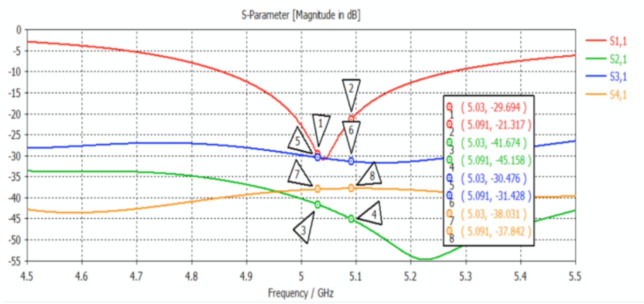

Fig. 7. Simulated S parameters for 2x2 configuration when one element is activated

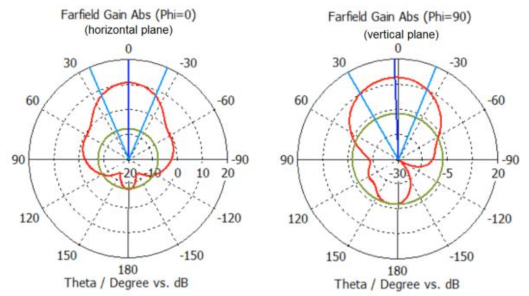

Fig. 8. Simulated horizontal and vertical plane radiation patterns for the 2x2 configuration

B. *Antenna array*

The designed antenna array structure is shown in Fig. 9. It is an active circular array with 8 elements. Different antennas are used for transmission and reception. For the receiver, active antennas with LNA (Low Noise Amplifier) are designed, and for the transmitter, active antennas with HPA (High Power Amplifier) are used.

When N elements are activated, antenna gain can be calculated by using Equation (1), in which, E_i represents the magnitude of the E field of the i-element [5].

$$G_{Total} = G_{element} + 20\log\left(\frac{|\sum_{i=1}^{N} E_i|}{|E_1|}\right) - 10logN \quad (1)$$

Three conditions are simulated for a better comparison and analysis, including two adjacent switched-on elements without phase shifters, three successive switched-on elements without phase shifter and three successive switched-on elements with 1-bit phase shifters to compensate the errors associated to the orientation of the antenna elements. As for the transmitter antenna, EIRP (Equivalent Isotropically Radiated Power) is calculated using the Equation (2), where P_{TX} is the power obtained at the output of the HPA of each active transmitter chain.

$$EIRP(dBm) = G_{Total}(dBi) + P_{TX}(dBm) + 10logN \quad (2)$$

The EIRP simulation results with Matlab are shown in Fig. 10, considering a P_{TX} of 30 dBm. As to the same colour, the upper line is for θ = 0º, whereas the other one is for θ = 25º, which is the required margin in elevation. The highest EIRP occurs when three radiating elements are fed with 1-bit phase shifters. However, this architecture is more complex and the cost is relatively high compared to the other two solutions. Therefore, the other two configurations are considered better choices.

As for the receiver antenna, gain is calculated, the simulation results with Matlab are shown in Fig. 11. As to the same colour, the upper line is for θ = 0º, whereas the other one is for = 25º. In terms of receiver antenna analysis, more gain is needed, so the red line is the best solution because it is much simpler.

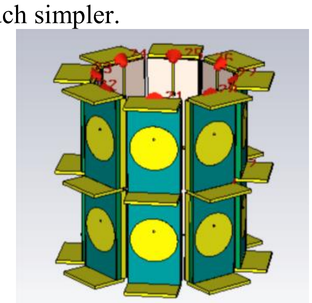

Fig. 9. Complete architecture of the designed antenna array

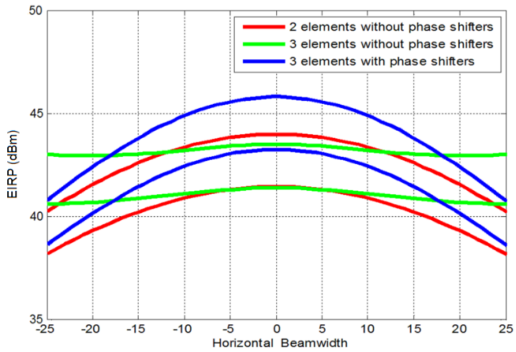

Fig. 10. Simulated EIRP for different configurations

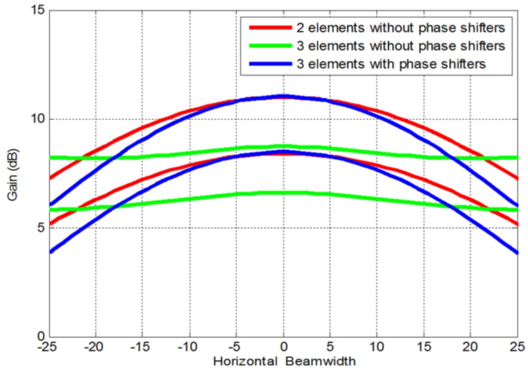

Fig. 11. Simulated gain for different configuration.

IV. RF Front End

The RF front end is one of the most important parts of our design, because it communicates antenna with modems. Main specifications of the system are described in Table I.

First, modems have a sensibility in aerial condition of -95 dBm. Modems use spread spectrum and they require a SNR of -15 dB for a 230 kbps capacity and of -1.6 dB for a 5 Mbps capacity. Their maximum output power is 30 dBm.

The key point in the Tx block is the P1dB of the amplifier. Our design use an amplifier with a gain of 26 dB that is too much if modems are working to the maximum power and consequently a variable attenuator is used to reduce it. Amplifier has a 32 dBm of P1dB, that it is enough to transmit 30 dBm from each element of the antenna.

The critical point in the receiver shown in Fig. 12 is the noise factor and the gain of the chain. Using this structure, our system measures a global noise factor of about 2.76 dB.

TABLE I
SPECIFICATIONS OF RF FRONT END

System bandwidth	80 MHz
Modem sensibility	-95 dBm
Noise Factor	2.76 dB
Receiver chain gain	26.1 dB
Transmission chain output power	30 dBm
Tx-Rx isolation	35 dB

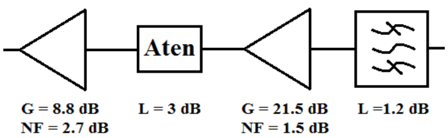

Fig. 12. Specification of the receiver chain

The other point is the gain because the noise due to the antenna and receiver chain should be higher than the noise generated by UAV engine in the modems. This is because UAV noise is uniform and independent from the power of the received signal. Therefore, a minimum gain of 20 dB is required in the receiver chain. A gain of 26.1 dB is achieved with two amplifiers, the filter and a 3 dB π attenuator.

One of the worst problems is the isolation between Rx and Tx antennas, because if it is too low, interference from Tx could saturate amplifier chain in receiver. For this reason, isolation between antennas must be at least 35 dB.

The battery drain is desirable to be as low as possible, consequently our amplifiers use 5 V as DC voltage.

Finally, considering two active radiating elements without phase shifters for transmission and reception, which achieve an EIRP of 44 dBm and a gain of 11 dB at the main lobe direction, the free-space path loss for a 70 km distance, a 80 MHz bandwidth, a 290 K antenna noise temperature and the noise figure of the receiver chain, the estimated SNR of the link is about 3.76 dB. This SNR provides a margin to allow a 5 Mbps capacity for different relative positions and attitudes of the UAVs. This capacity is suitable for the transmission of a high definition video stream.

V. Conclusions

This paper has presented the design of an UAV communications system based on smart antennas to provide air-air connections and extend the autonomy of current medium-sized UAVs by using a second UAV as a relay. This system provides a bidirectional low capacity link for telemetry and telecommands and a high-capacity downlink for video. During the design, simplicity has been taken into account above all. The antenna module consists of two circular arrays, one for reception and the other for transmission, with eight vertically polarized circular patches that are selectively activated depending on the desired direction of the beam. Measurements will be carried out in order to characterize the operation of the system.

VI. Acknowledgments

The authors would like to thank Unmanned Solutions, S.A. for its support to this work. The authors also want to acknowledge the Madrid Region Government for financing the project S2013/ICE-3000 SPADERADAR-CM and the Spanish Government for its support to the projects TEC2014-55735-C3-1-R and TEC2014-53815-R.

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